

Searches for  $t\bar{t}H$  and  $tH$  with  $H \rightarrow b\bar{b}$ MATTHIAS SCHRÖDER  
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The associated production of a Higgs boson with a top quark-antiquark pair ( $t\bar{t}H$  production) or with a single top quark ( $tH$  production) allows a direct measurement of the top-Higgs-Yukawa coupling with minimal model dependence. In this article, recent results of searches for  $t\bar{t}H$  and  $tH$  production in the  $H \rightarrow b\bar{b}$  channel performed by the ATLAS and CMS experiments are reviewed. The analyses use pp collision data collected at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of up to  $13.2 \text{ fb}^{-1}$ .

PRESENTED AT

9<sup>th</sup> International Workshop on Top Quark Physics  
Olomouc, Czech Republic, September 19–23, 2016

# 1 Introduction

The coupling of the Higgs (H) boson to the top (t) quark is of particular interest. In the Standard Model (SM), it is of Yukawa type with a strength  $y_t$  proportional to the t-quark mass, and hence, it is exceptionally large. Thus,  $y_t$  contributes dominantly to various loop processes both in the SM and also in models of new physics. The current value of  $y_t$  is dominated by indirect constraints derived from measurements of the gluon-gluon fusion H-boson production and the  $H \rightarrow \gamma\gamma$  decay rate and depends on the assumption of absence of new particle contributions to the loop amplitudes.

The associated production of a H boson with a t quark-antiquark pair ( $t\bar{t}H$  production) or with a single t quark (tH production), on the other hand, allows a direct measurement of  $y_t$  with minimal model dependence, cf. Fig. 1. However, the SM cross section of both processes is relatively small with approximately 0.5 pb and 90 fb at 13 TeV centre-of-mass energy, respectively, making this a difficult measurement. The bottom (b) quark-antiquark final state of the H boson benefits from a large branching ratio. At the same time, the relatively poor jet-energy resolution and the huge combinatorial uncertainty in the event reconstruction require to use multivariate analysis methods to discriminate signal from background processes, where the signal cross section is determined with a fit of the discriminant distributions to the data.

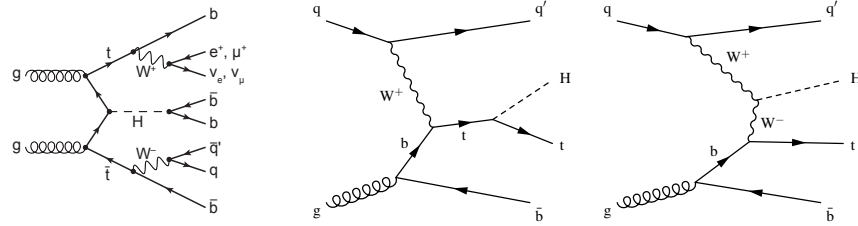


Figure 1: Example leading-order Feynman diagrams contributing to the lepton+jets-channel  $t\bar{t}H(b\bar{b})$  (left) and the t-channel  $tH(b\bar{b})$  production (centre, right) [1, 2].

## 2 Searches for $t\bar{t}H(b\bar{b})$ production

Both CMS [3] and ATLAS [4] have performed searches for  $t\bar{t}H$ ,  $H \rightarrow b\bar{b}$ , production in the dilepton and lepton+jets final states of the  $t\bar{t}$  system at 13 TeV centre-of-mass energy: CMS has published the first analysis at 13 TeV using  $2.7 \text{ fb}^{-1}$  of data collected in 2015 [1], ATLAS has published an analysis using  $13.2 \text{ fb}^{-1}$  of 2015 and 2016 data [5].

Events are generally selected by requiring in the dilepton channel 2 isolated, oppositely-charged leptons (electrons or muons) and  $\geq 3$  jets,  $\geq 2$  of which are identified as coming from b quarks (b-tagged), and in the lepton+jets channel 1 isolated lepton and  $\geq 4$  jets,  $\geq 2$  of which are b-tagged. Additional, channel-dependent



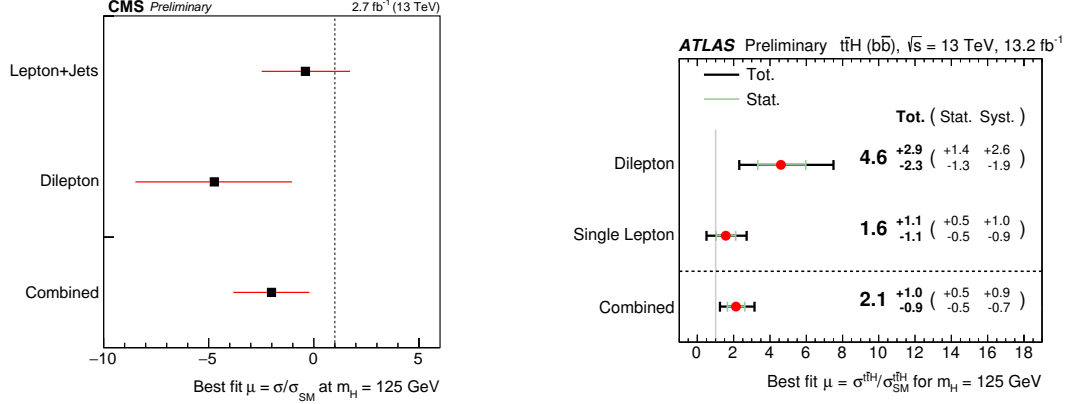


Figure 3: Best-fit values of the signal-strength modifier  $\mu$  with their one standard deviation confidence intervals of the CMS [1] (left) and ATLAS [5] (right) analyses.

system  $p_T$  spectra of the NNLO calculation, including resummation at NNLL accuracy. Events with  $\geq 1$  additional b jets are reweighted to a SHERPA+OPENLOOPS prediction at next-to-leading order, using the CT10 4-flavour-scheme PDF set. Uncertainties on the  $t\bar{t} + \text{HF}$  processes are assigned based on the differences observed to a MADGRAPH5 aMC@NLO prediction, and the overall normalisation of the contributions from  $t\bar{t} + \geq 1$  b or c jets events is left freely floating in the final fit.

Both analyses employ multivariate methods to combine in each category the information of several variables, such as kinematic properties or invariant masses of combinations of jets and leptons, into a final discriminating variable, cf. Fig. 2 (right). The signal cross section  $\sigma$  is determined with a binned fit of the background and signal discriminant distributions to the data, where the uncertainties, which affect the rate and the shape of the distributions, are taken into account via nuisance parameters.

At CMS, boosted decision trees (BDTs) and, in several categories, also a matrix-element-method (MEM) classifier are used. The latter is a likelihood of the event kinematics under the signal or background hypothesis, taking into account response and acceptance effects, which is constructed to separate against the important  $t\bar{t} + b\bar{b}$  background. Depending on the category, the MEM variable is an input to the BDT or events are further separated into two sub-categories with low and high BDT-output and the MEM is used as final discriminant in each sub-category. In a novel approach, also dedicated techniques are applied to reconstruct events in which the H boson and the hadronically decaying t quark are fairly boosted, resulting in reduced combinatorics in the jet assignment and thus a better event reconstruction efficiency.

At ATLAS, a two-staged multivariate approach is used in the signal-enriched categories. A BDT is trained to assign the jets to the partons from the H-boson and t-quark decays under the signal hypothesis. Based on this event reconstruction,

additional separating variables, such as the invariant mass of the b jets from the H-boson decay, are computed. They are used together with reconstruction-independent variables as input to a classification BDT or an artificial neural network that separate signal from background events. In the signal-depleted categories in the lepton+jets channel (dilepton channel) the scalar sum of the jet (and lepton)  $p_T$  is used, which aims at constraining the systematic uncertainties of the background model.

CMS obtains a signal strength  $\mu = \sigma/\sigma_{\text{SM}}$  relative to the SM expectation of  $\mu = -2.0^{+1.8}_{-1.8}$  with  $2.7 \text{ fb}^{-1}$  of data and ATLAS of  $\mu = 2.1^{+1.0}_{-0.9}$  with  $13.2 \text{ fb}^{-1}$  of data, cf. Fig. 3, which are compatible with the SM expectation within 1.7 standard deviations. These correspond to observed (expected) upper limits on  $\mu$  at the 95% confidence level (C.L.) of 2.6 ( $3.6^{+1.6}_{-1.1}$ ) for CMS and 4.0 ( $1.9^{+0.9}_{-0.5}$ ) for ATLAS.

### 3 Search for $tH(b\bar{b})$ production

At leading order,  $tH$  production occurs predominantly via t-channel and associated  $tW$  production. In both cases, the H boson can be emitted either from the t quark or the intermediate W boson, cf. Fig. 1. The amplitudes of both contributions interfere depending on the coupling of the H boson to the t quark and to the W boson, expressed hereafter as coupling strengths  $\kappa_t$  and  $\kappa_V$  relative to the SM expectation, respectively. Hence,  $tH$  production is sensitive to both the magnitude and the sign of  $y_t$ . The interference is destructive in the SM, but can in general also be constructive resulting in an enhanced  $tH$  production cross section, e.g. by a factor ten for  $\kappa_t = -1$  and  $\kappa_V = +1$  (inverted top coupling scenario, ITC).

CMS has performed a search for  $tH$  production in the  $H \rightarrow b\bar{b}$  final state with a leptonically decaying t quark, using  $2.3 \text{ fb}^{-1}$  of data at 13 TeV. Events are selected requiring 1 isolated lepton and  $\geq 3$  b-tagged jets, targeting the b quarks from the H boson and t quark decay. Events are further divided into two exclusive signal regions, one with 3 and one with 4 b-tagged jets as well as 1 additional non b-tagged jet in each case, targeting the fourth b jet, which often falls out of acceptance, and the additional light-flavour jet, cf. Fig. 1. The dominant SM background in both signal regions stems from  $t\bar{t}$  + jets production, which is modelled as for the CMS  $t\bar{t}H$  search.

Events are reconstructed under both the signal and the  $t\bar{t}$  + jets hypothesis, assigning the jets to the final-state quarks depending on the output of two dedicated BDTs that take into account b-tagging and jet kinematic information. Based on the specific event reconstruction, separating variables, such as the  $p_T$  of the H boson, are computed. These, together with reconstruction-independent variables, are used as input to a classification BDT that separates signal and background, cf. Fig. 4 (left).

Limits on the signal cross section are obtained for 51 different points in the  $(\kappa_t, \kappa_V)$  parameter space by fitting the corresponding BDT output distributions to the data, simultaneously in the two signal regions. Since the kinematic properties of the signal

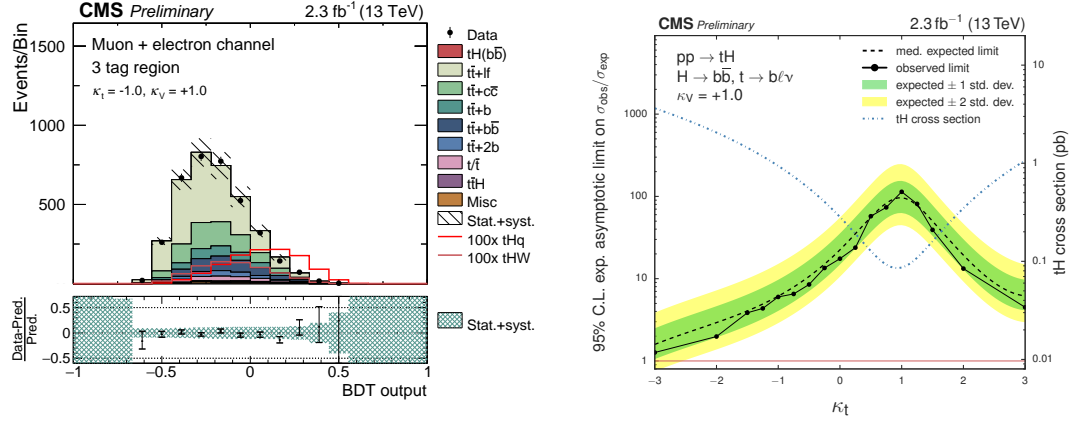


Figure 4: Classification BDT output for the ITC case (left), after the fit to the data. The  $t\bar{t}$  + jets background is divided by the flavour of the additional jets, and the  $t\bar{t}H$  contributions in both considered production channels, normalised to 100 times the expectation, are superimposed. Also shown are the observed and expected upper limits on the signal production cross section as a function of  $\kappa_t$  for  $\kappa_V = +1$  (right) [2].

events depend on  $\kappa_t$  and  $\kappa_V$ , dedicated BDT trainings are performed for each point. The results for  $\kappa_V = +1$  are shown in Fig. 4 (right), further results for  $\kappa_V = +0.5$  and  $+1.5$  have been derived [2]. For the SM and the ITC scenario, observed (expected) upper limits at 95% C.L. of  $113.7$  ( $98.6^{+60.6}_{-34.6}$ ) times the SM expectation and  $6.0$  ( $6.4^{+3.7}_{-2.2}$ ) times the ITC expectation, respectively, are obtained.

## 4 Summary

First searches by CMS and ATLAS for  $t\bar{t}H(b\bar{b})$  production at 13 TeV result in a signal strength of  $\mu = -2.0^{+1.8}_{-1.8}$  with  $2.7 \text{ fb}^{-1}$  and  $\mu = 2.1^{+1.0}_{-0.9}$  with  $13.2 \text{ fb}^{-1}$  of data. A 95% C.L. upper limit on  $t\bar{t}H(b\bar{b})$  production with inverted couplings  $\kappa_t = -1$  of 6.0 times the expectation is observed by CMS using  $2.3 \text{ fb}^{-1}$  of data. The achieved sensitivities are close to or surpass the ones at 8 TeV with only a fraction of the data.

## References

- [1] CMS Collaboration, CMS-PAS-HIG-16-004 (2016).
- [2] CMS Collaboration, CMS-PAS-HIG-16-019 (2016).
- [3] CMS Collaboration, JINST 3 (2008) S08004.
- [4] ATLAS Collaboration, JINST 3 (2008) S08003.
- [5] ATLAS Collaboration, ATLAS-CONF-2016-080 (2016).